# USE OF CORRELATION TECHNIQUES IN AUTOMATIC DETECTION OF THERMAL PLUMES IN THE AIR LAYER ADJACENT TO NATURAL WATER WAVES

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# United States
# Naval Postgraduate School

# THESIS

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IN THE
AIR LAYER ADJACENT TO NATURAL WATER WAVES

by

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Thesis Advisor: J. D. Campbell

June 1971

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# Use of Correlation Techniques in Automatic Detection of Thermal Plumes in the Air Layer Adjacent to Natural Water Waves

by

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ABSTRACT

Pattern recognition of temperature fluctuations, representing plumes, occurring in data recorded in the atmospheric boundary layer was performed utilizing predefined characteristics of these phenomena. An averaged, normalized plume was computed based on the characteristics of ten previously identified plumes. This standard plume consisted of two components or curves and a component-by-component correlation was made of this standard plume with various data sets, each set containing temperature information recorded at two different heights. A product curve was then formed from the two correlation curves and used to identify plumes automatically. A plume was said to have been detected if the product curve exceeded a previously selected threshold. The accuracy of this detection method was determined by visual inspection of the same records by a meteorologist. Approximately 73 per cent of all plume occurrences in the data sets were detected which indicates the appropriateness of this method of pattern recognition for plume detection.

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# I. INTRODUCTION

Patterns may be broadly classified into two major groups; man-made and natural. Man-made patterns, such as the characters in an alphabet, consist of symbols which are designed and produced by humans. Natural patterns, such as cloud formations, are those found in nature to which man assigns names.

Pattern recognition is an emerging field of study with many applications to both man-made and natural patterns. It is not a cohesive discipline in its own right, however, but a vast collection of highly varied problems. Any technique which contributes to the solution of any of these problems can be considered an integral part of pattern recognition. These techniques may be statistical, adaptive, or heuristic depending upon the special characteristics of the pattern type under consideration.

A natural pattern of interest occurs within traces of temperature data recorded in the atmospheric boundary layer. This pattern appears as an intermittent asymmetrical saw-tooth "pulse" of large amplitude and always occurs as a positive fluctuation in the ambient temperature. The occurrence of these pulses in data of this kind has been reported by Taylor (1958), Priestly (1959) and Webb (1965). Taylor suggested that the pulses are due to organized thermal structures, or "plumes", contained within the complex turbulent flow. A schematic of such a plume appears in Figure 1.

Temperature inhomogeneities in the non-ionized atmosphere, such as those associated with plumes, are among several mechanisms which

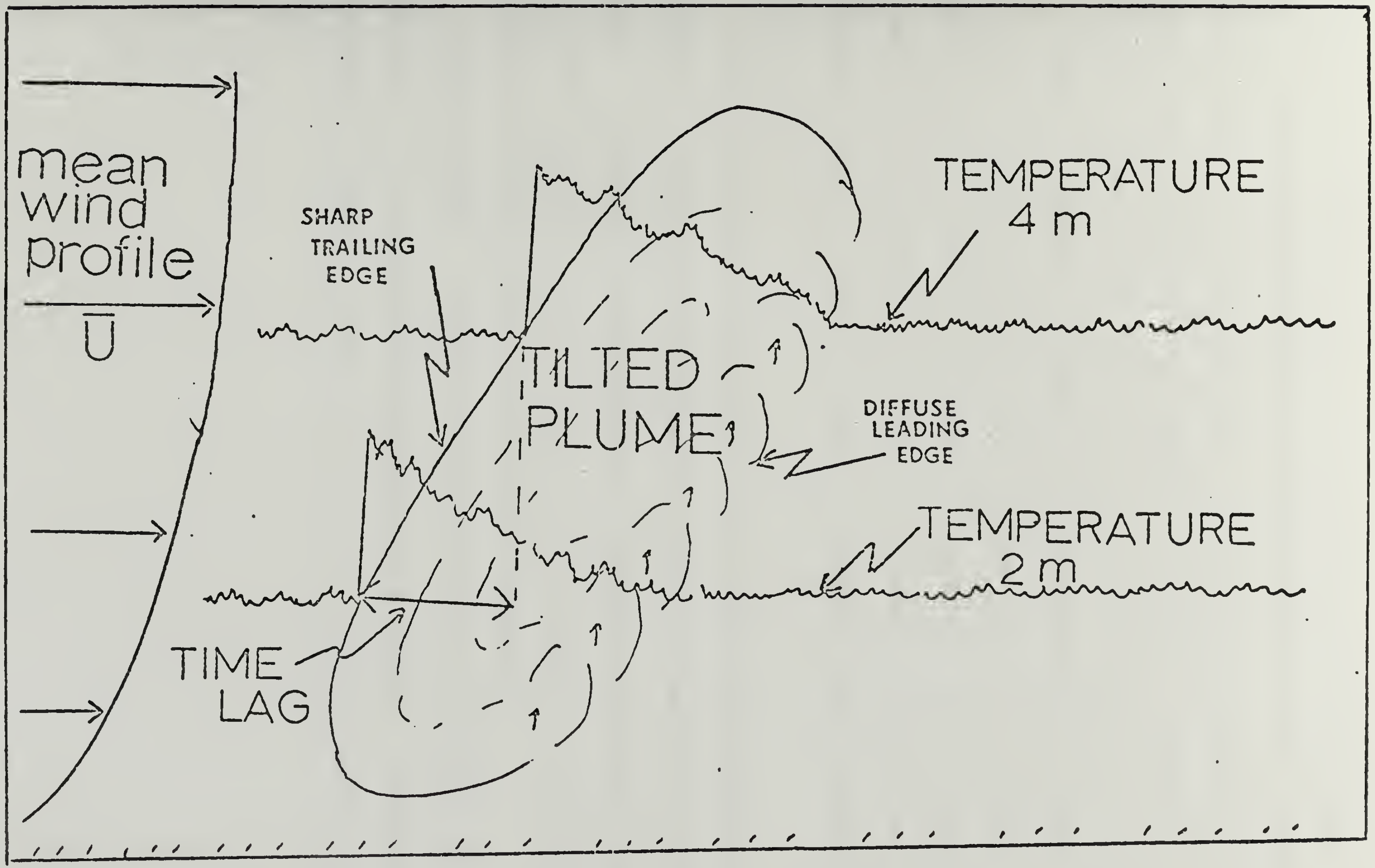



Figure 1. Schematic of Thermal Plume (after Gill, 1971)

distort the propagation of an electromagnetic wave over a line-of-sight path. Strohbehn (1968) placed these distortions into three groups: (1) absorption; (2) refraction; and (3) random scattering due to random fluctuations in the dielectric constant which causes variations in the amplitude, phase, angle-of-arrival, and polarization of the wave.

The last of these distortions is of interest because the final accuracy of radar systems, communication networks, and other systems may be limited by propagation characteristics. Furthermore, propagation effects that are negligible at lower frequencies may be dominant in higher frequency systems such as in the millimeter and optical bands.

Plumes are also of interest for their role in the exchange of heat, moisture, and momentum between the earth's surface and the atmosphere. Priestly (1959) contends that knowledge of the role of plumes in transferring heat and water vapor to the atmosphere is essential to properly define boundary fluxes of these quantities.

Many scientific disciplines require statistics describing plume phenomena. The versatility and usefulness of pattern recognition techniques and results underscore its value in this data-gathering task.

## II. DESCRIPTION OF DATA

All measurements of temperature fluctuations used in this study were originally recorded by Kenneth L. Davidson in 1968 under a grant administered by the Office of Naval Research. Davidson (1970) describes in detail the acquisition and processing of these data. The techniques and procedures used by him in this data-gathering task were studied to insure that the appearance of plumes represented actual geo-physical phenomena and were not artifically introduced via equipment irregularities. An abridged version of his description is presented in this chapter.

### A. FIELD SITE

All data were obtained on Lake Michigan from a fixed U. S. Lake Survey Research Tower located in 15 meters of water 1.6 km from shore near Muskegon, Michigan (Figure 2). The uncomplicated bottom and shoreline features present in this area were reasons for selecting this site. The lake is surrounded by first order weather stations which permitted the acquisition of complementary meteorological information during measurement periods.

### B. DESCRIPTION OF TOWER

Figure 3 shows the general construction of the research tower and its instrumentation during acquisition of the data used in this study. The structure was designed to achieve stability and to minimize disturbance to the airflow and water motions. The various sensor mountings on the tower enabled collection of turbulent velocity, wind, and wave measurements as well as temperature data. Temperature measurements in the air were made simultaneously at two heights.

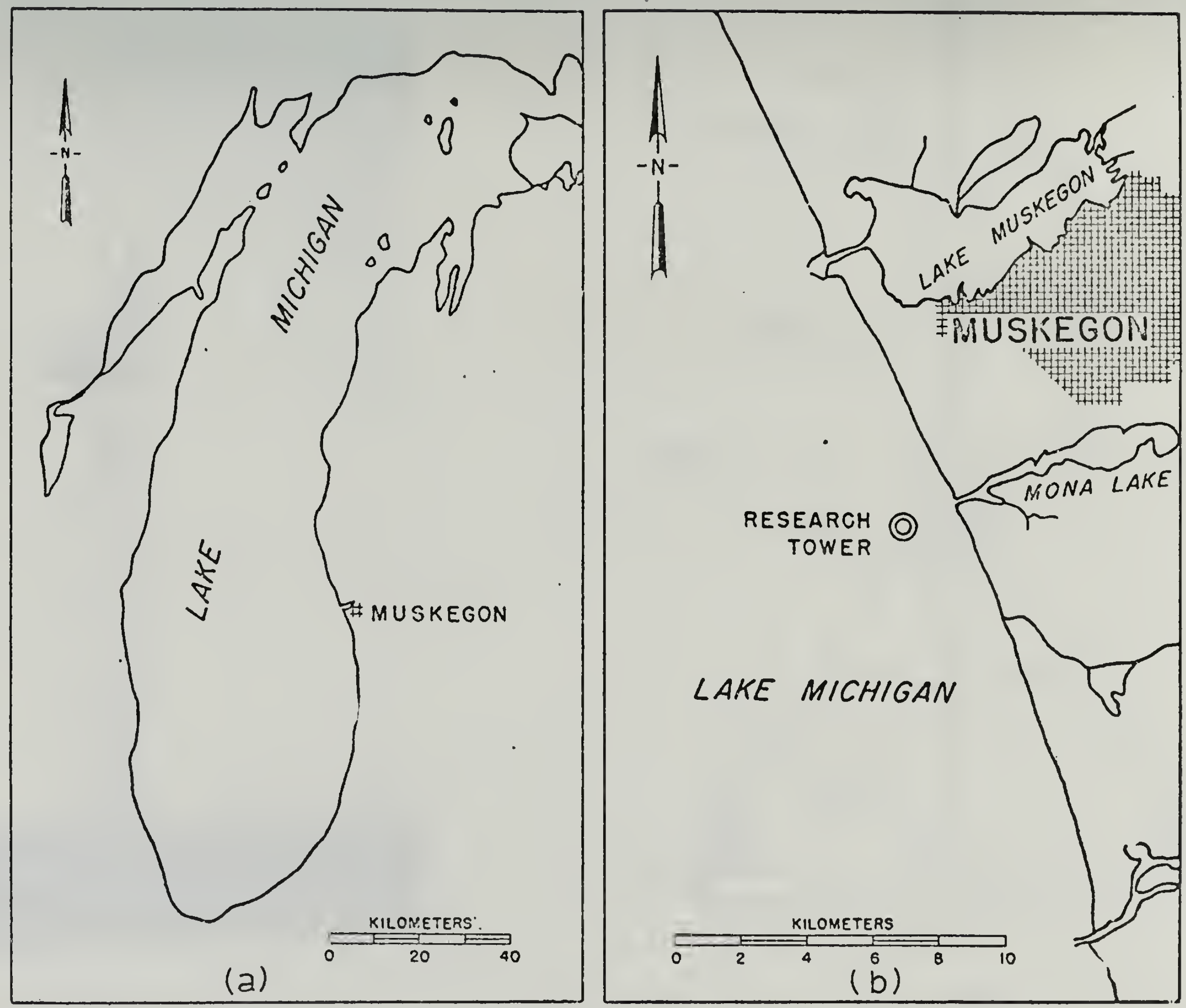
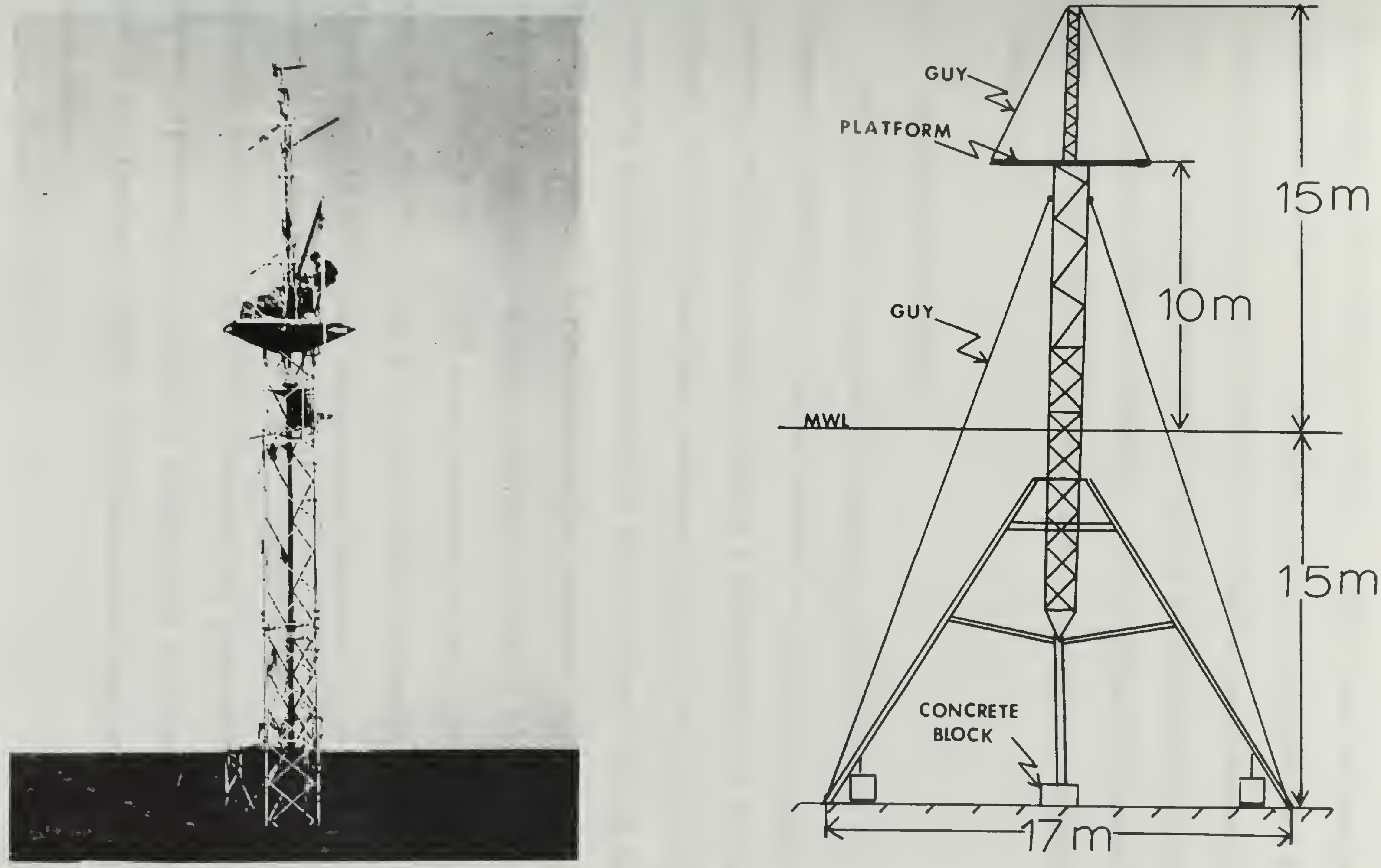



Figure 2. Location of U.S. Lake Survey Research Tower;
(a) Lake Michigan, (b) tower site near Muskegon, Michigan.
(after Davidson, 1970)




(a) (b)

Figure 3. Research tower; (a) as instrumented during experiment, (b) schematic showing underwater tripod support structure. (after Davidson, 1970)

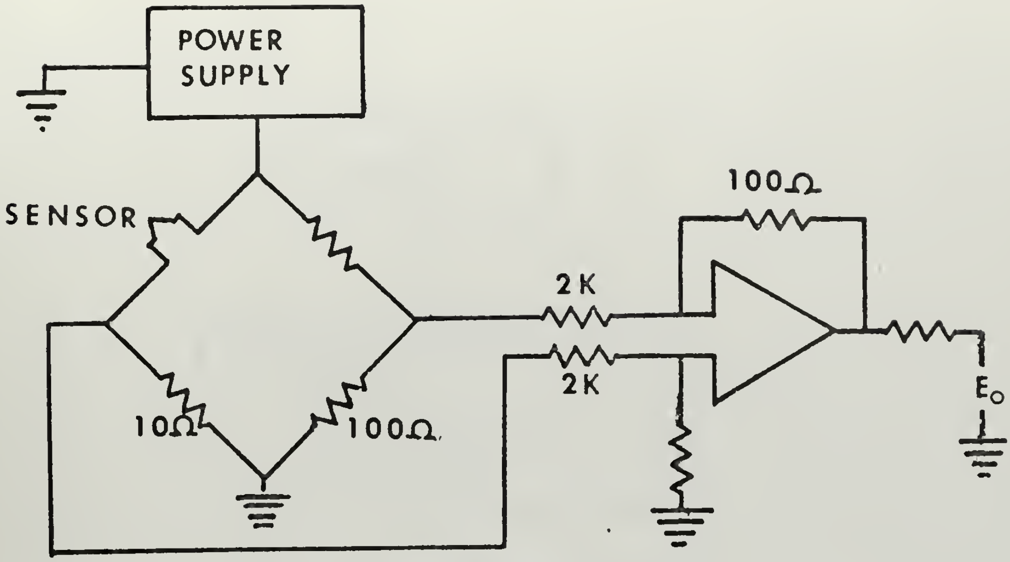
## C. EQUIPMENT SENSORS FOR TEMPERATURE MEASUREMENT

A resistance thermometer was used to measure temperature fluctuations. The sensor, a 30 ohm, .00015 inch tungsten wire, .16 inches long, is part of a constant-current circuit and with a small filament current (approximately 2 ma) serves as a resistance thermometer. The bridge unbalance caused by a temperature fluctuation, and hence a sensor resistance change, was amplified 2500 times for the output signal. A block diagram of the bridge circuit is illustrated in Figure 4.

## D. RECORDING SYSTEM

All data were recorded on magnetic tape in analog form using frequency modulation. A seven channel recorder was used in this process, with all recordings made at a tape speed of 3 3/4 inches per second. The corresponding recorded frequency was D. C. to 625 Hz. Two of the seven channels available were allocated for the two temperature sensors. A schematic of the complete recording system (recorders and preamplifiers) appears in Figure 5.

Calibration signals were recorded on all channels at the beginning and end of each tape and at any point where recording was interrupted. These signals served as indicators of recorder drift as well as noise level and were used during digitizing procedures. Constant monitoring of amplified and pre-amplified signals was performed with a dual channel oscilloscope in order to evaluate the electronic outputs and to insure that the input signals would not exceed amplifier or recorder input limits.



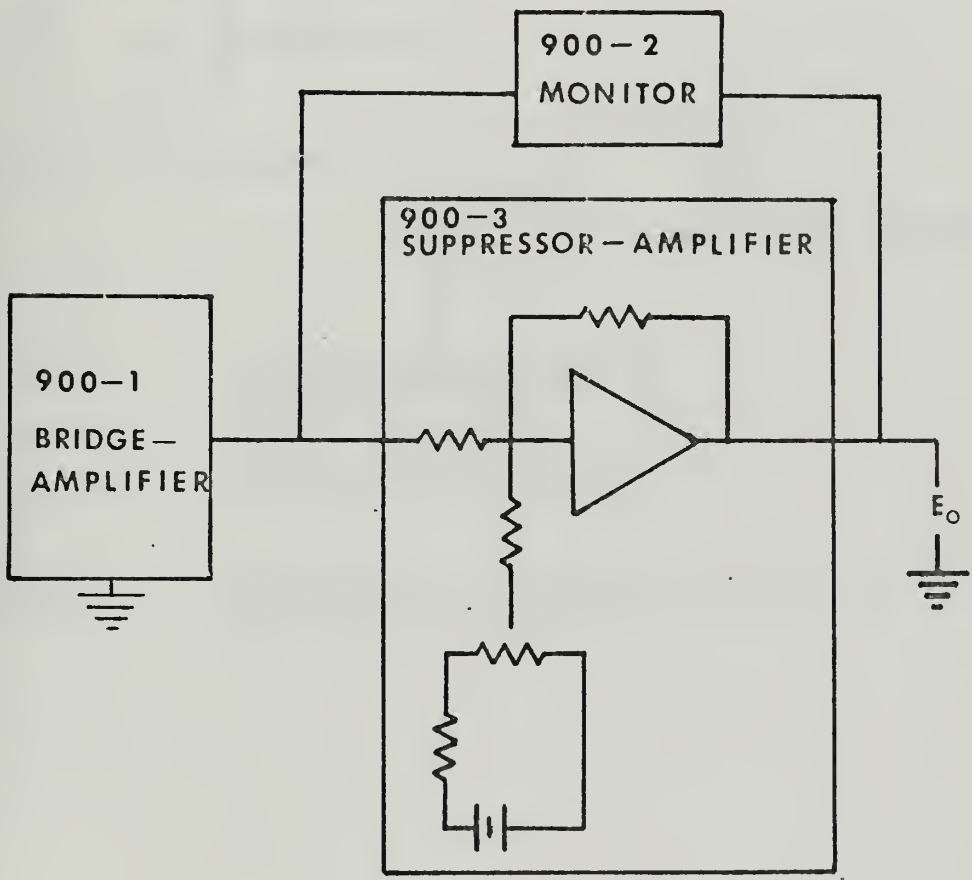




Figure 4. Temperature system bridge-amplifier (constant currrent); Flow Corporation System, Series 900. (after Davidson, 1970)

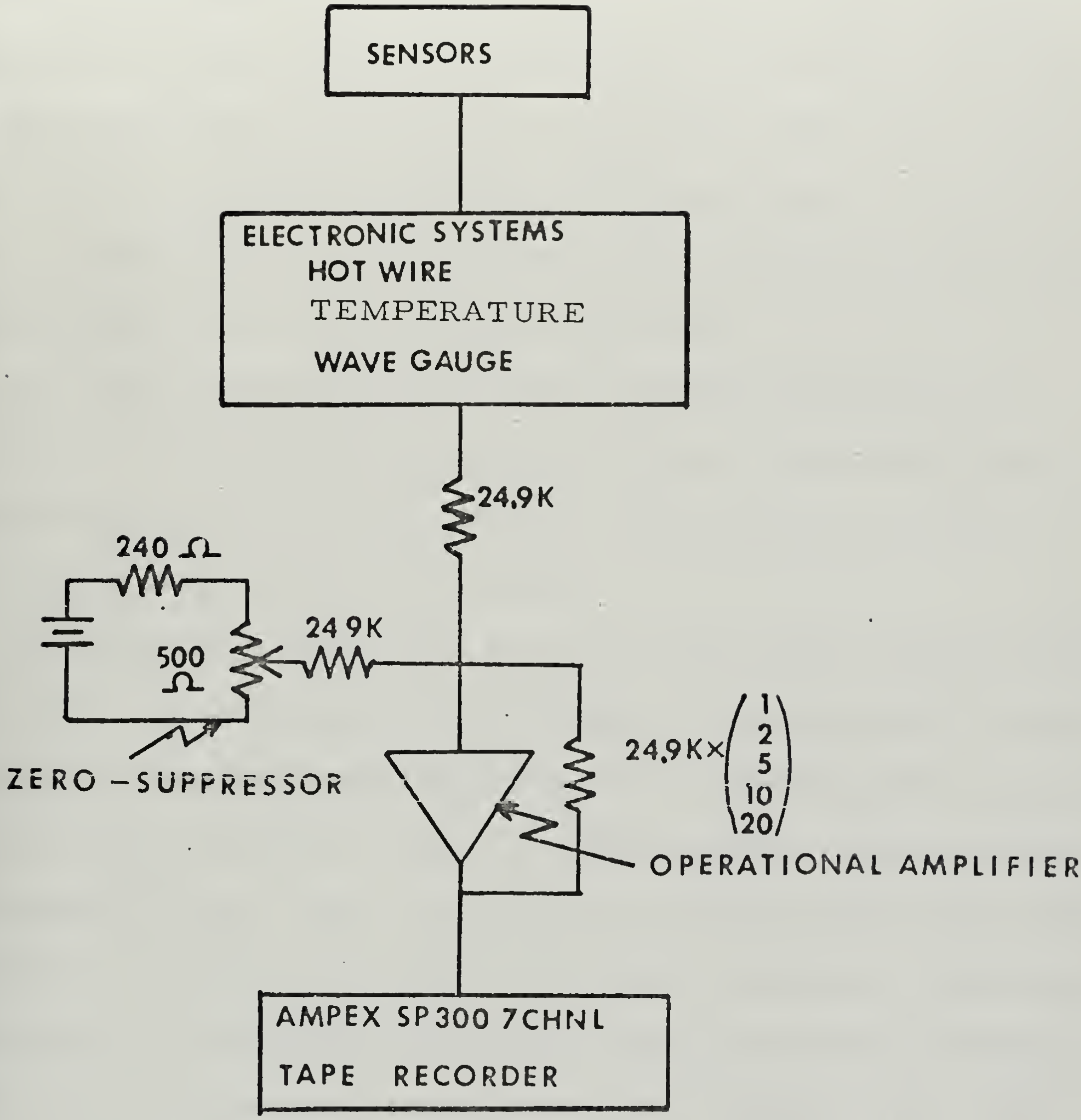



Figure 5. Schematic of recording system components. (after Davidson, 1970)

## E. DATA REDUCTION

Steps performed to digitize the data are summarized in Figure 6. Because the recorded signals could range only from -2 to +2 volts and the analog-to-digital converter had a range from -100 to +100 volts, a gain of 50 was applied to all signals. Calibration signals recorded before, during and after measurement periods were used to adjust for gain and drift errors in the recorder electronics.

Data from all channels were lowpass filtered through identical second-order Butterworth analog filters. Figure 7 shows the analog circuit and the energy response function. A sampling rate of 300 points per second was used in digitizing.

The temperature fluctuations of interest were those with frequencies below 10 Hz, so additional numerical filtering was performed. A feed-forward filter was employed and Figure 8 shows its magnitude - squared frequency response characteristics. Also included are the tap weights and transfer function, $H(\omega)$, for the filter. Since the digital filter output was only computed for every tenth point in the original data, the data out of this numerical filter consisted of 30 samples per second of a signal with frequency components ranging from D. C. to about 10 Hz. Since plumes appear to have no significant frequency components above 2.5 Hz, the data were filtered again (numerically) to extract every sixth point resulting in a filter output of 5 points per second. This was the data rate used in this study. The response curve for this filter appears in Figure 9.

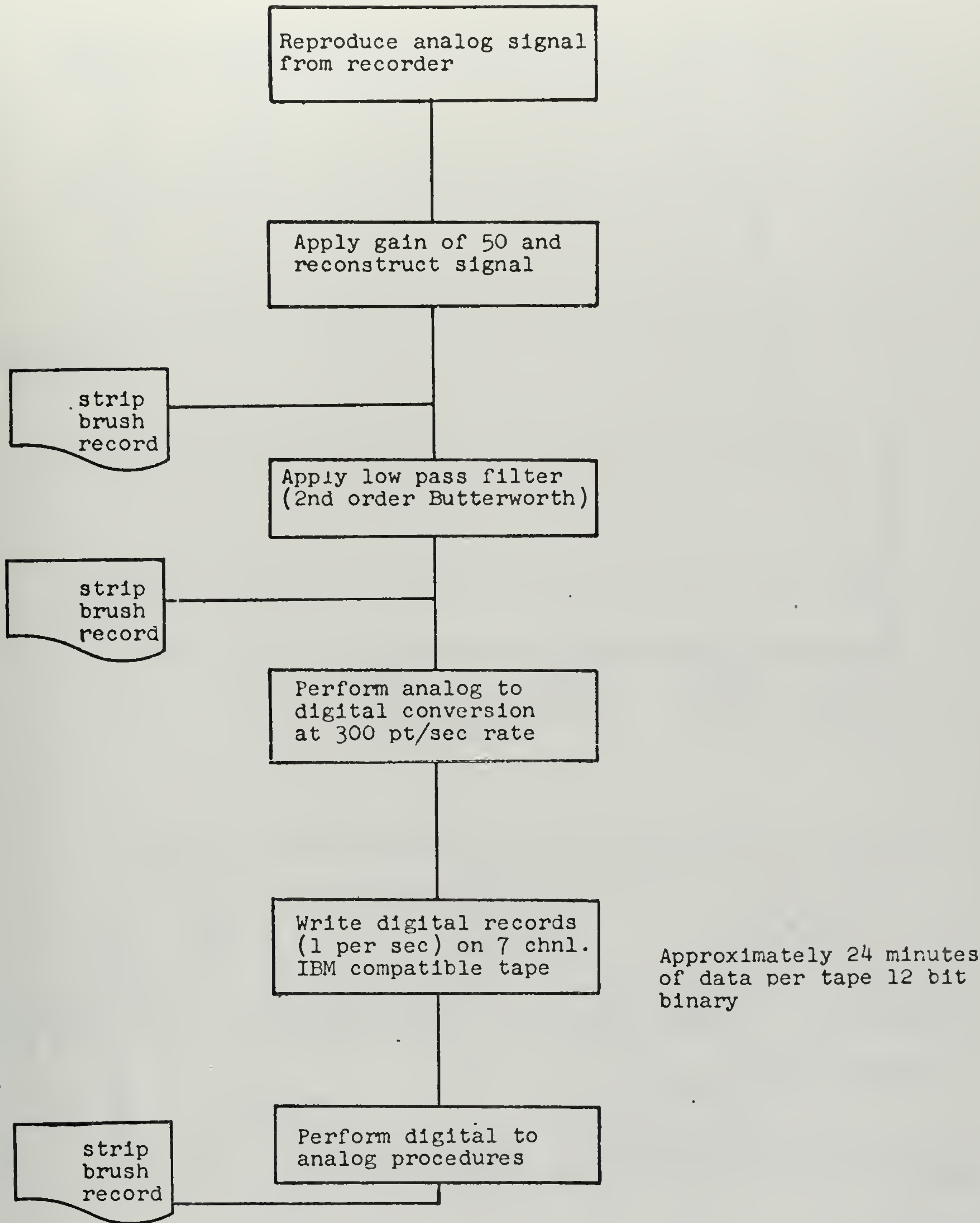
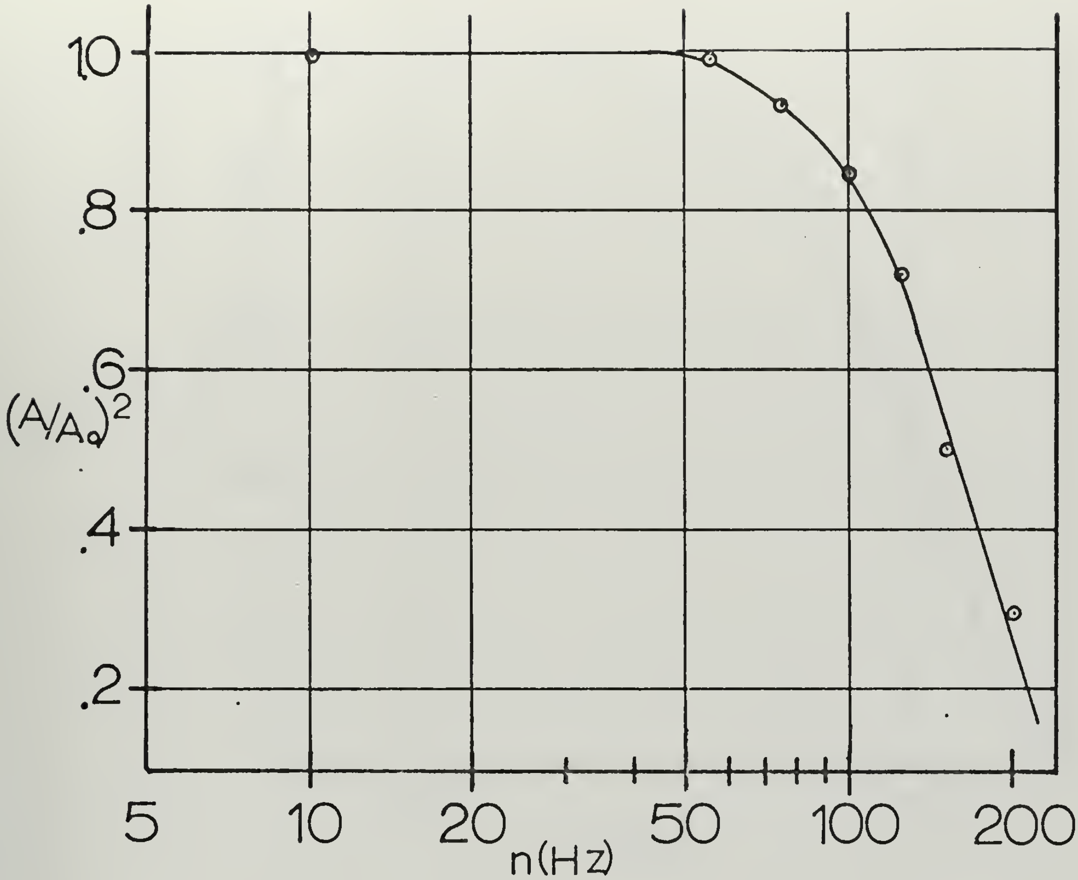



Figure 6. Flow chart of procedures in analog to digital processing. (after Davidson, 1970)




ANALOG LOW-PASS FILTER (2nd order Butterworth)

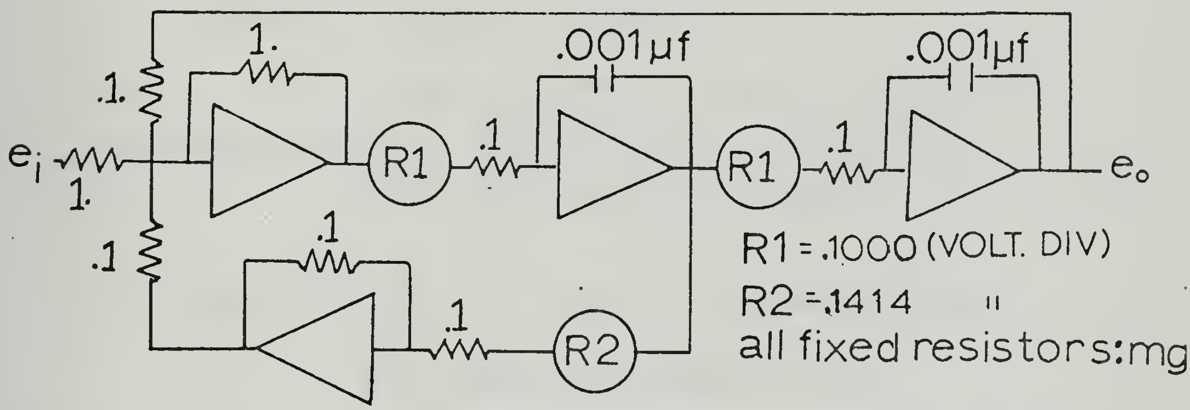
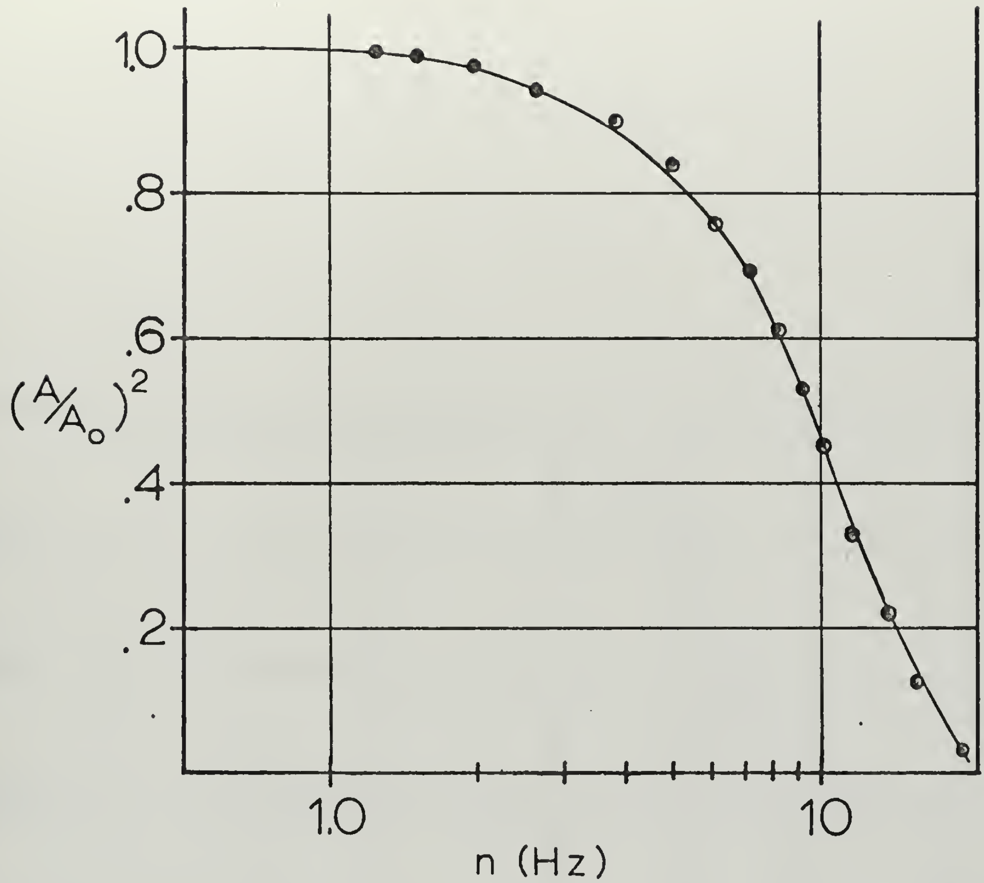



Figure 7. Frequency response curve, $(A/A_o)^2$, and circuit employed in analog low-pass filtering. (after Davidson, 1970)




i) $H(\omega) = h_o + 2\sum_{n=1}^{N/2} h_n \cos(n\Delta t\omega)$

where $\omega$ = radian frequency;

$\Delta t$ = time interval betweeen data points

ii) $h(n\ t) = \frac{\pi}{2n\ t}\left[\frac{\sin(\omega_t n\Delta t) + \sin(\omega_c n\Delta t)}{\pi^2 - (\omega_t - \omega_c)^2\ (n\Delta t)^2}\right]$

where: $\Sigma h_n$ = 1 to insure no change in mean

N = number of weights (21)

$\omega_c$ = cut-off frequency ($\omega_c/2\pi$ = 10 Hz)

$\omega_t$ = terminal frequency ($\omega_c/2\pi$ = 20 Hz)

Figure 8. Frequency response, $(A/A_o)^2$, curve and weight functions employed in numerical low-pass filter. (after Davidson, 1970)

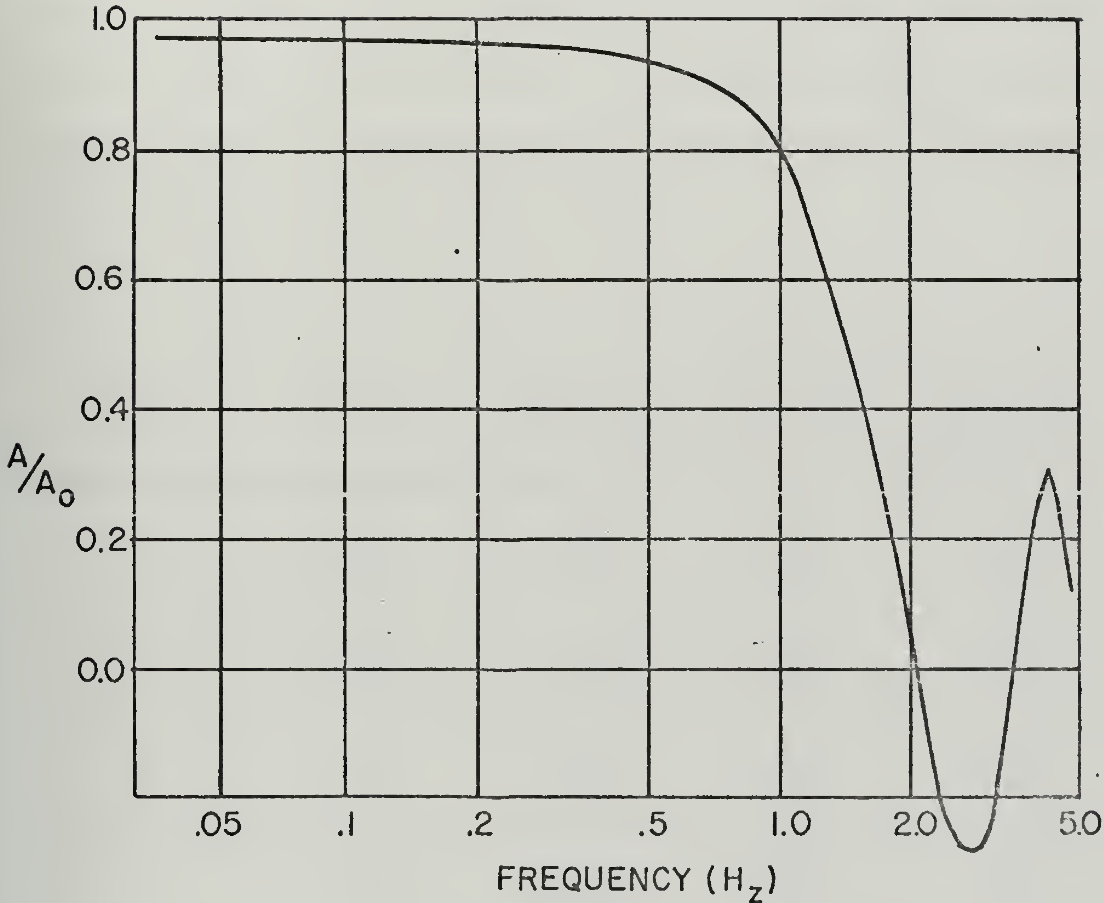



Figure 9. Frequency response curve, $A/A_o$, for final numerical lowpass filter.

## III. THEORETICAL CONSIDERATIONS

Visual examination of temperature traces containing plumes indicates a striking resemblance to displays of communication signals entrained in noise. Since the optimum detector of such signals in white Gaussian noise is a matched filter, attention was directed toward this technique as a detection method for plumes. Accordingly, the data used in this study were analyzed to determine their distributions. The results of this analysis are summarized in Table I.

| Data Period | Height Level (m) | Standard Deviation | Skewness*: $\bar{e^3}/(\bar{e^2})^{3/2}$ | Kurtosis: $\bar{e^4}/(\bar{e^2})^2$ |
|---|---|---|---|---|
| 1 | 1.0<br>2.0 | 0.19<br>0.16 | 0.31<br>0.38 | 2.67<br>2.52 |
| 2 | 1.0<br>2.0 | 0.17<br>0.15 | 0.36<br>0.62 | 2.68<br>2.97 |
| 3 | 1.0<br>2.0 | 0.18<br>0.16 | 0.28<br>0.49 | 2.78<br>2.85 |
| 4 | 1.5<br>4.0 | 0.29<br>0.23 | 0.32<br>-0.09 | 2.50<br>2.33 |

* $\bar{e}$ is the average value of the fluctuations

Table I. Statistics of Temperature Data

The tabulated values of skewness in Table I indicate that the data do not possess a Gaussian distribution. The noise itself may be normally distributed, however, and the combination of plume plus

noise may skew the distribution. Therefore, the use of the matched filter approach to plume detection was considered.

The matched filter concept applied to pattern recognition can be described as a form of template matching. The categorization process is then equivalent to a component-by-component correlation of an unknown sample with a known sample or pattern. Although correlation methods can be shown to be optimal only under certain very restrictive conditions on the distributions in question, these methods were considered the logical point at which to initiate attempts at solution of the plume recognition problem. Furthermore, since the plume detection problem is a binary one, either the plume exists in the random turbulent flow or it does not, the correlation method is particularly appropriate. If the measurement space contained many distinct patterns to be categorized, then different approaches for delineating hyperplanes and establishing clustering criteria should be considered. Correlation techniques, although comparatively simple, occupy a valid position in the framework of pattern recognition.

## IV. EXPERIMENTAL PROCEDURE

The correlation method of pattern recognition requires a known template sample to compare against unknown samples. Applied to plume detection, the template becomes an averaged, "standard" plume. Salient plume characteristics considered in the computation of this standard plume are listed below:

(1) a gradual rise of the temperature data followed by a sharp drop, producing an asymmetrical saw-tooth or triangular trace,

(2) simultaneous occurrence of the pattern in temperature traces from two measurement levels arranged in a plumb line,

(3) four to six seconds duration of each pattern,

(4) separation of patterns by quiescent periods,

(5) fluctuations contributing to the pattern are always positive with respect to the recorded trace's preferred mean value.

CAL-COMP plots were obtained for one 18 minute data set and, using the above characteristics, a total of ten plumes were identified. The exact point where the sharp drop occurred in each plume was determined and a computer program was developed to compute an averaged, normalized, standard plume. The flow chart of this program appears as Figure 10 and the standard, normalized plume defined by this procedure is shown in Figure 11.

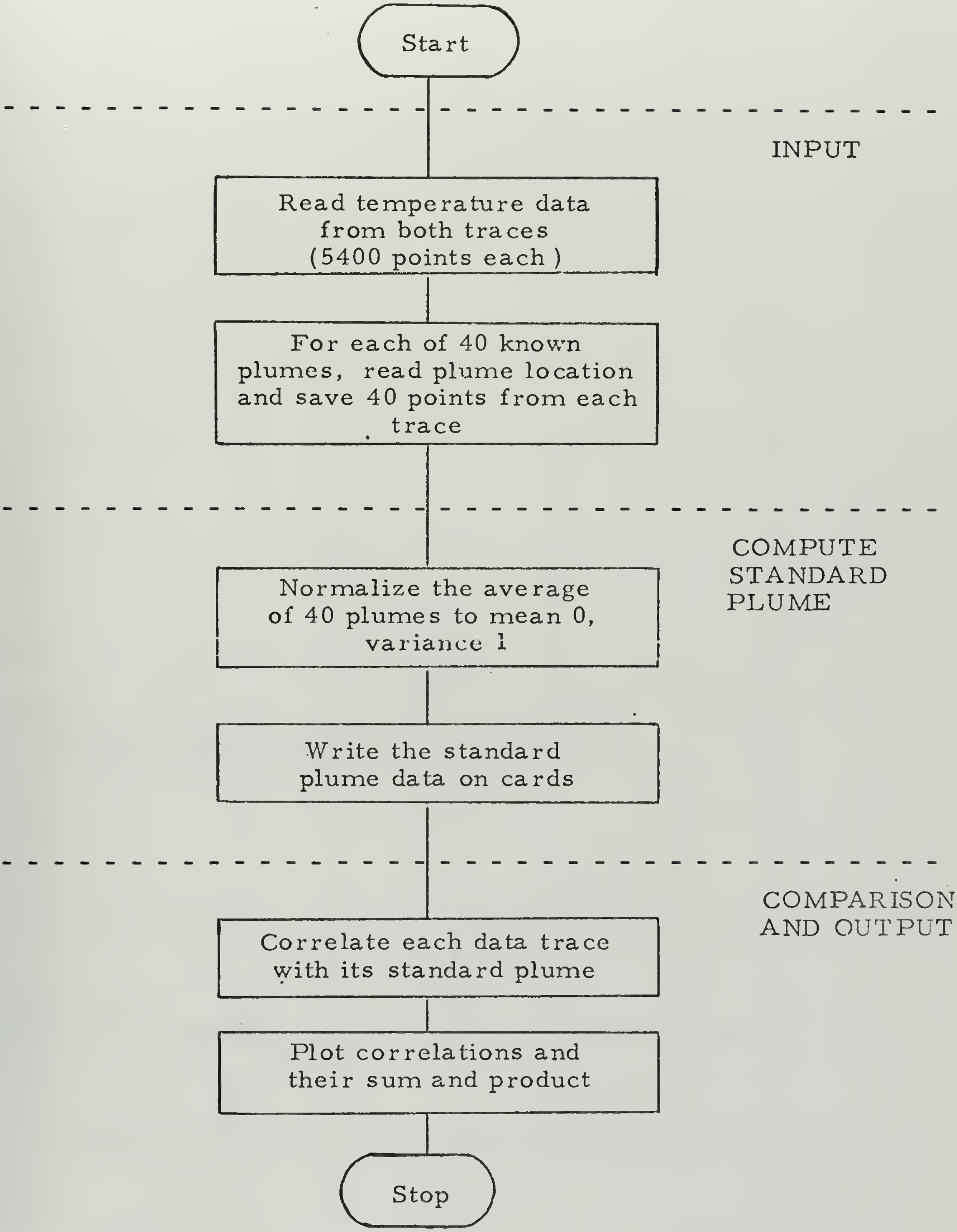



Figure 10. Flow chart of program to compute standard plume and correlate it with data sets.

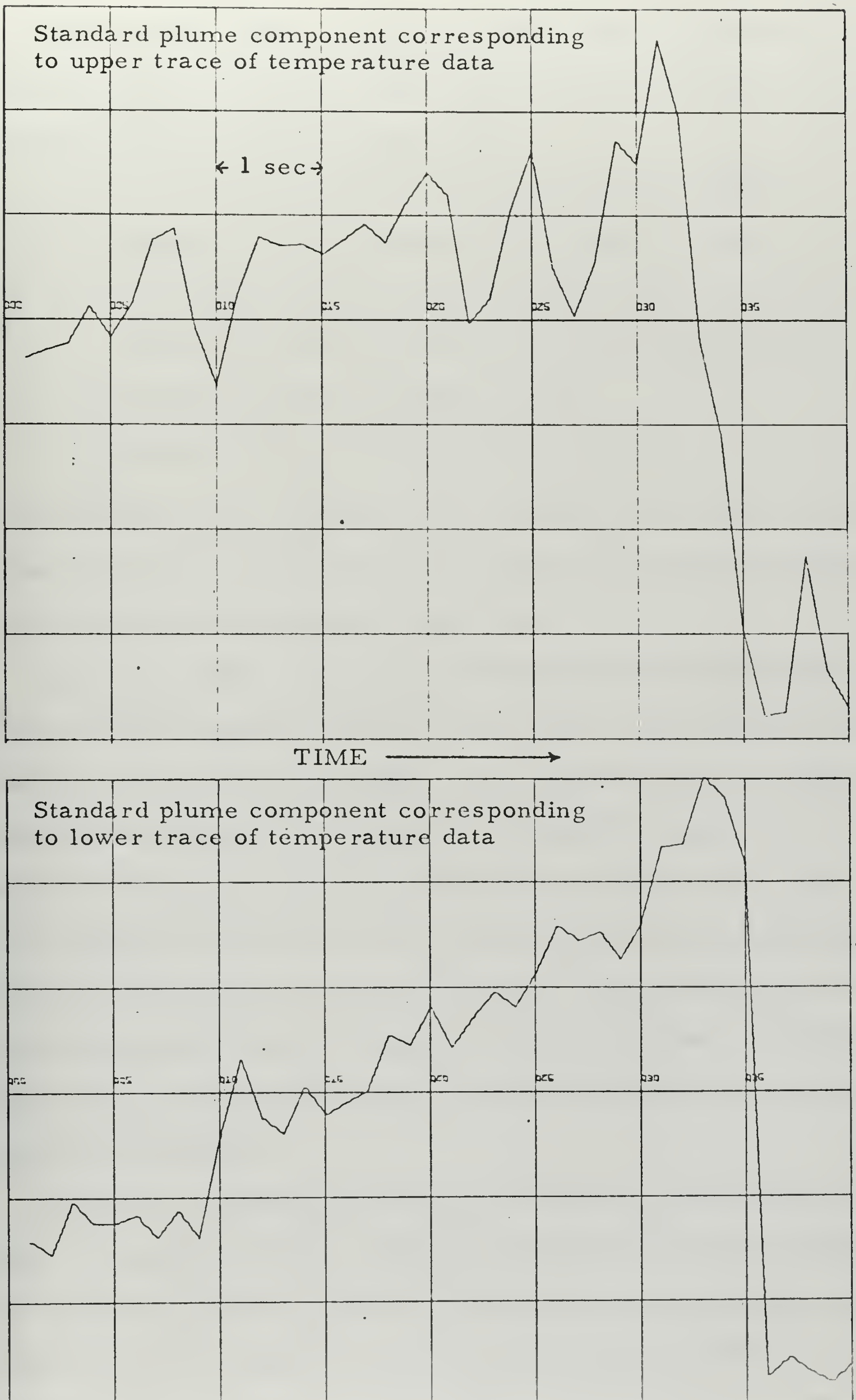



Figure 11. Plot of Standard Plume

This standard plume, consisting of two traces to correspond with the two heights at which the temperature fluctuations were measured, was correlated with the data in four ways:

(1) correlation of the first component of the standard plume with the top trace of the temperature data,

(2) correlation of the second component of the standard plume with the bottom trace of the temperature data,

(3) addition of both correlation traces,

(4) multiplication of both correlation traces.

The correlation traces obtained were positioned next to their respective temperature traces and the varying degrees of correlation magnitude were noted in relation to plume occurrence.

Correlation plots were initially obtained on the same data set from which the standard plume was computed. This data set can be considered as "training set" data. The standard plume was then correlated with various "test set" data. To establish confidence in the validity of the standard plume, two different test sets were used. The first consisted of data acquired the same day and at the same height levels as the training set. Meteorological conditions were also uniform during both periods. The second test set data was obtained on a different day, at different heights, and with different meteorological conditions prevailing.

Kenneth L. Davidson, Assistant Professor of Meteorology at the Naval Postgraduate School, subjectively analyzed the traces obtained and identified plume occurrences. Thresholds for low, medium and high probability of detection were then determined from the correlation plots.

# V. PRESENTATION OF DATA

A total of four measurement periods, each eighteen minutes in length, were considered in this study. The heights of the two temperature sensors above the mean water level were the same for periods 1, 2, and 3 but were different for period 4. Data from period 1 were used as the training set, data from periods 2 and 3 were combined to form the first test set and data from period 4 were used as the second test set. Pertinent information concerning these periods is summarized in Table II.

| Period | Date | Time (EST) | Measurement Level (meters) | Significant Wave Height* $H_{1/3}$ (cm) |
|---|---|---|---|---|
| 1 | September 27 (1968) | 1120-1138 | 1.0 and 2.0 | 42 |
| 2 | September 27 (1968) | 1140-1158 | 1.0 and 2.0 | 46 |
| 3 | September 27 (1968) | 1200-1218 | 1.0 and 2.0 | 44 |
| 4 | September 26 (1968) | 1355-1413 | 1.5 and 4.0 | 38 |

*$H_{1/3}$ = four times the standard deviation of the water surface. The value of $H_{1/3}$ is a good estimate of the average height (crest to trough) of the highest one-third waves in the record.

Table II. Description of Sampling Intervals and Physical Conditions During Data Acquisition.

## A. WEATHER CONDITIONS DURING SAMPLING INTERVALS

Light to moderate wind speeds prevailed during the first three periods. The mean wind velocity at the 4 meter level at the onset of sampling period 1 was approximately 3 meters per second and gradually increased to about 3.5 meters per second at the completion of sampling period 3. Hydrostatic conditions were unstable since the water surface temperature was 3°C higher than the air temperature at 4.0 meters. During sampling period 4 the wind speed was higher, approximately 5.5 meters per second at the 4 meter level. Hydrostatic conditions were also unstable during this period with the water temperature being about 5°C higher than the air temperature at 4.0 meters.

## B. DISPLAY OF DATA

CAL-COMP plots were obtained of all data sets to facilitate plume recognition. Two plots, corresponding to the two heights at which the data were recorded, were traced on each graph. Each graph was fifteen inches in length and contained nine hundred points per plot which represented three minutes of data. Six graphs were needed, therefore, to plot data from each eighteen minute period.

Traces defining the standard plume were then correlated with their respective temperature traces in each data set producing a pair of correlation curves for each data set. The sum and product of these two correlation curves were also obtained. Comparison of all correlation curves thus obtained showed that the product curve provided the best display for plume detection. Typical examples of the temperature traces investigated and their corresponding product of correlation curves are reproduced in Figures 12, 13, and 14.

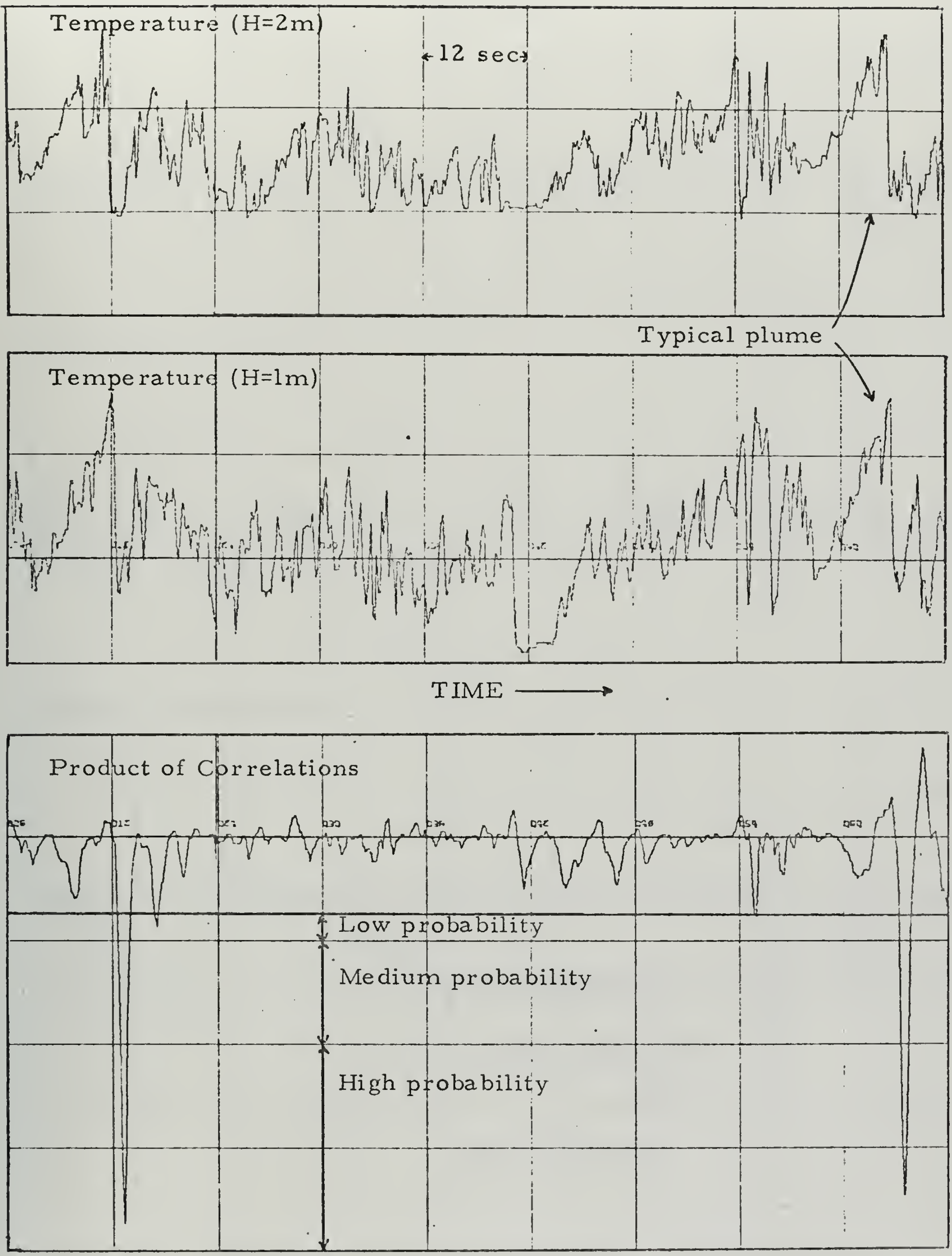



Figure 12. Examples of Traces from Training Set Data.

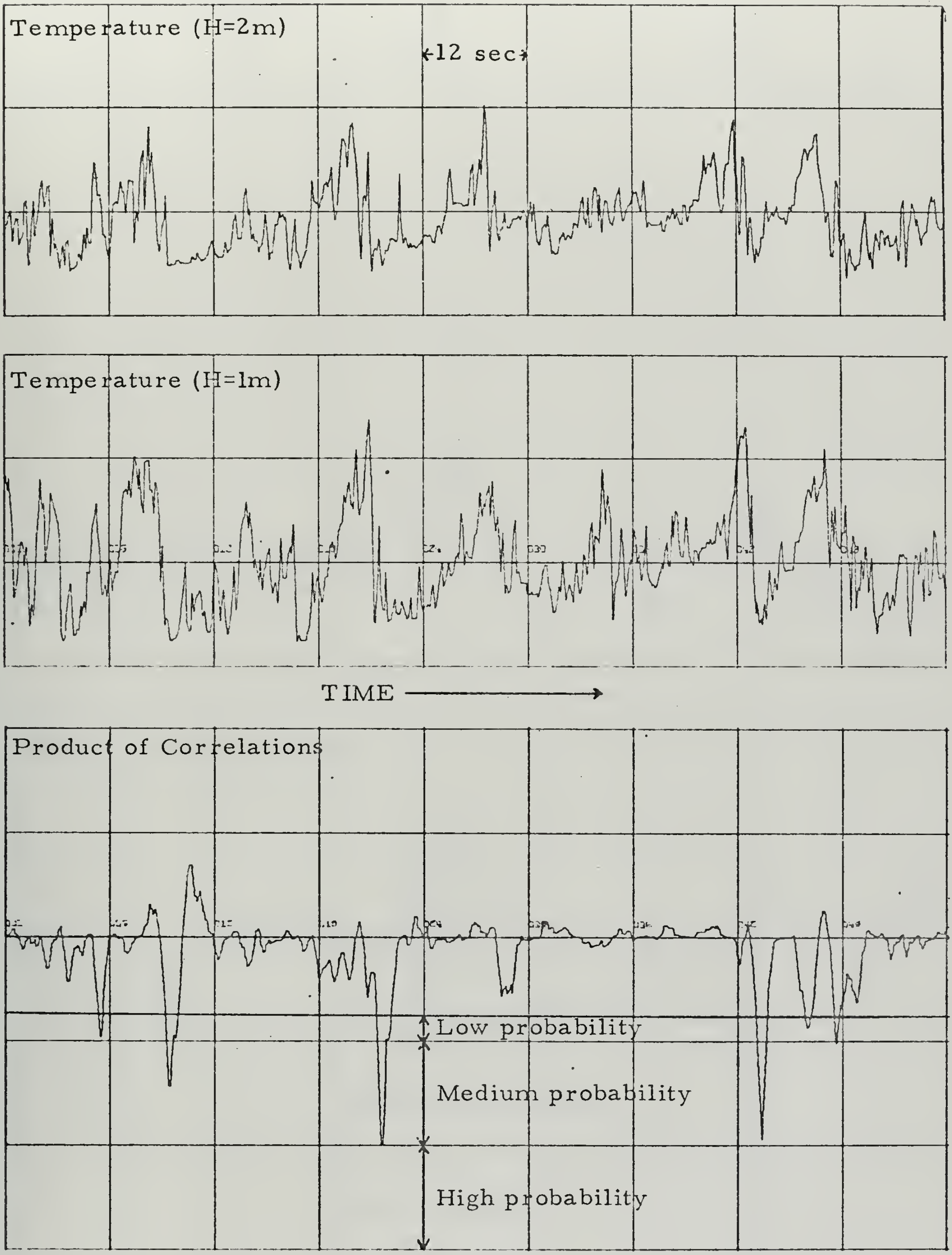



Figure 13. Examples of traces obtained from first test set data.

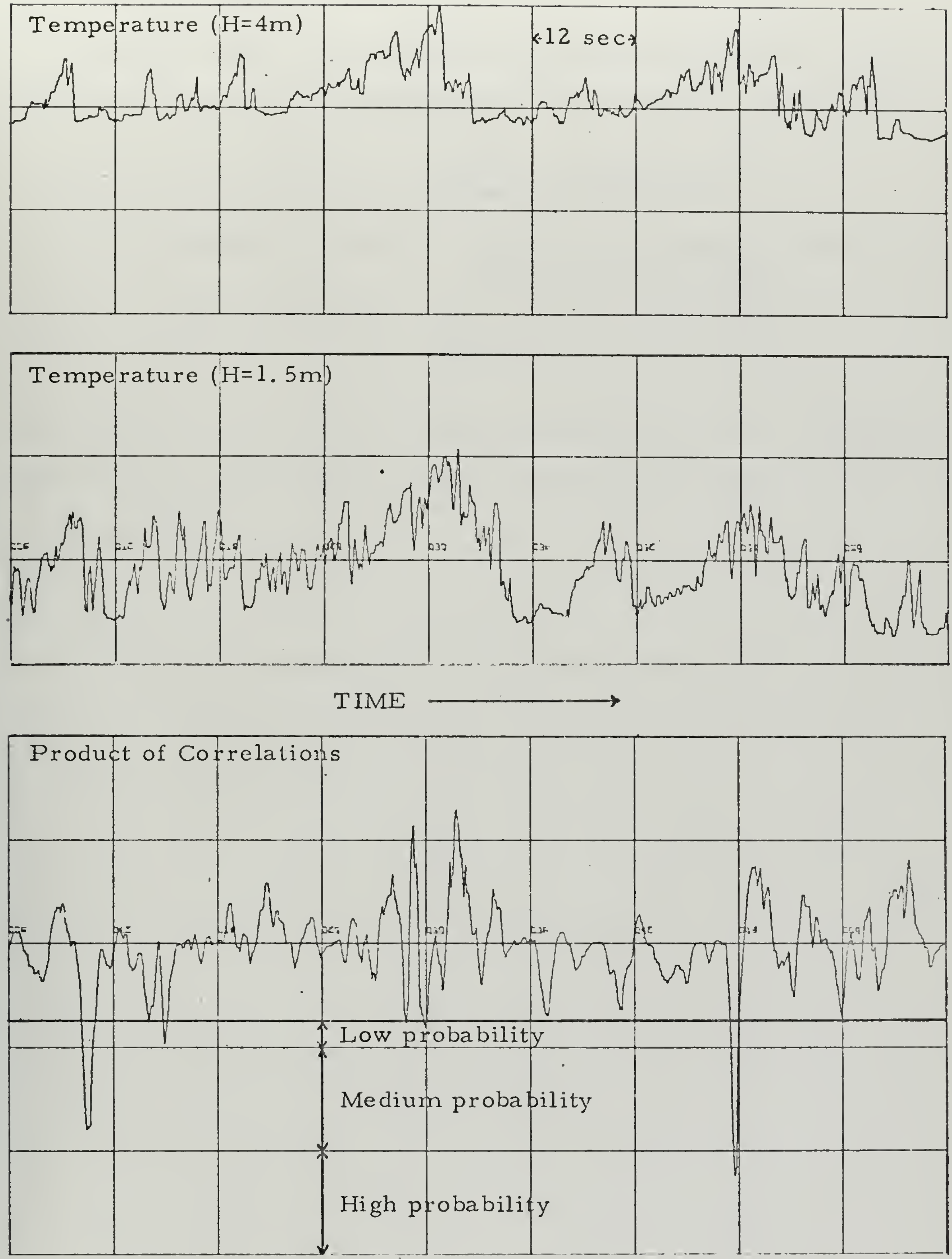



Figure 14. Examples of traces obtained from second test set data.

## C. TABULATION OF RESULTS

Using the scale on the product of correlation curve, the following thresholds for various probabilities of plume detection were assigned:

Low probability - product curve peaks between 300 units and 400 units,

Medium probability - product curve peaks between 400 units and 800 units,

High probability - product curve peaks above 800 units.

The accuracy of each level of detection probability for the training set data and the two test sets of data is summarized in Tables III, IV, and V respectively.

| Probability of Correct Detection | Number of Plumes Indicated | Correct Identification | Incorrect Identification | Percentage of Accuracy |
|---|---|---|---|---|
| LOW | 14 | 8 | 6 | 57.1 |
| MEDIUM | 9 | 6 | 3 | 66.7 |
| HIGH | 3 | 3 | 0 | 100.0 |
| Totals | 26 | 17 | 9 | 65.4 |

SUMMARY:

(1) There were a total of 23 plumes visually observed in this data set of which 17 were detected on the correlation plots. The overall percentage of detection was 74.0%.

(2) The total number of incorrect plume detections was 9. The percentage of incorrect detections by probability category is as follows:

Low probability: 66.7%

Medium probability: 33.3%

High probability: 0%

(3) A total of 6 plumes were visually observed which were not detected by the correlation plots.

Table III. Analysis of Results on Training Set Data.

| Probability of Correct Detection | Number of Plumes Indicated | Correct Identification | Incorrect Identification | Percentage of Accuracy |
|---|---|---|---|---|
| LOW | 26 | 12 | 14 | 46.4 |
| MEDIUM | 27 | 17 | 10 | 63.0 |
| HIGH | 4 | 4 | 0 | 100.0 |
| Totals | 57 | 33 | 24 | 57.8 |

SUMMARY:

(1) There were a total of 45 plumes visually observed in this data set of which 33 were detected on the correlation plots. The overall percentage of detection was 73.3%.

(2) The total number of incorrect plume detections was 24. The percentage of incorrect detections by probability category is as follows:

Low probability: 58.3%

Medium probability: 41.7%

High probability: 0%

(3) A total of 12 plumes were visually observed which were not detected by the correlation plots.

Table IV. Analysis of Results on First Test Set Data.

| Probability of Correct Detection | Number of Plumes Indicated | Correct Identification | Incorrect Identification | Percentage of Accuracy |
|---|---|---|---|---|
| LOW | 21 | 11 | 10 | 52.3 |
| MEDIUM | 25 | 18 | 7 | 72.0 |
| HIGH | 2 | 2 | 0 | 100.0 |
| Totals | 48 | 31 | 17 | 64.5 |

SUMMARY:

(1) There were a total of 42 plumes visually observed in this data set of which 31 were detected on the correlation plots. The overall percentage of detection was 73.1%.

(2) The total number of incorrect plume detections was 17. The percentage of incorrect detections by probability category is as follows:

Low probability: 58.8%

Medium probability: 41.2%

High probability: 0%

(3) A total of 11 plumes were visually observed which were not detected by the correlation plots.

Table V. Analysis of Results on Second Test Set Data.

## VI. CONCLUSIONS

The percentage of correct plume detections provides justification for the selected correlation approach. Accuracy could be increased by further refinement of the standard plume. This could be accomplished by using more than ten known plumes to form the standard. Further extensions of this research might be to examine the possibility of using other pattern recognition techniques for improved plume detection. As an example, an adaptive approach could be employed whereby a standard plume would be modified by each newly-identified plume to provide the most representative or current pattern. Such a scheme might allow for plume detection under different weather conditions. However, the methods and results developed in this study appear to be quite useful in their present form.

Most procedures now used to study atmospheric turbulence depend upon assumptions that the processes are nearly random and stationary. These assumptions often lead to the use of spectral methods for examining the relationship between parameters contributing to heat flux (i. e., w and T) or momentum flux (i. e., u and w). The data being considered herein, however, show that a significant and persistent occurrence in supposedly random temperature fluctuations has been organized plumes. These are intermittent in their occurrence yet all have similar features which are identifiable. The intermittency of these plumes precludes the use of most techniques employed in atmospheric turbulence investigations for their study. In order to more accurately define the processes responsible for a significant amount

of heat flux near the surface, in this case over a water surface, new techniques such as pattern recognition methods are needed.

In conclusion, this study has yielded a new "coordinate" system with which to examine processes contributing to the exchange of sensible heat between the ocean and the atmosphere.

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13. ABSTRACT

Pattern recognition of temperature fluctuations, representing plumes, occurring in data recorded in the atmospheric boundary layer was performed utilizing predefined characteristics of these phenomena. An averaged, normalized plume was computed based on the characteristics of ten previously identified plumes. This standard plume consisted of two components or curves and a component-by-component correlation was made of this standard plume with various data sets, each set containing temperature information recorded at two different heights. A product curve was then formed from the two correlation curves and used to identify plumes automatically. A plume was said to have been detected if the product curve exceeded a previously selected threshold. The accuracy of this detection method was determined by visual inspection of the same records by a meteorologist. Approximately 73 per cent of all plume occurrences in the data sets were detected which indicates the appropriateness of this method of pattern recognition for plume detection.

| KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Pattern Recognition | | | | | | |
| Temperature Fluctuations | | | | | | |
| Atmospheric Boundary Layer | | | | | | |
| Matched Filter Detection | | | | | | |
| Correlation | | | | | | |

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S66393 Sokol
c.1 Use of correlation
technique in automatic
detection of thermal
plumes in the air layer
adjacent to natural
waterwaves.